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ZORA URL: <https://doi.org/10.5167/uzh-77957>

Conference or Workshop Item

Published Version

Originally published at:

Wolfgramm, Bettina; Seiler, Bruno; Kneubühler, Mathias; Liniger, Hanspeter (2006). Spatial assessment of erosion and its impact on soil fertility in the Tajik foothills. In: 26th EARSeL Symposium on New Developments and Challenges in Remote Sensing, Warschau (PL), 29 May 2006 - 2 June 2006. Millpress, 331-341.

Spatial assessment of erosion and its impact on soil fertility in the Tajik foothills

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Keywords: soil erosion, soil fertility indicators, diffuse reflectance spectroscopy, Tajikistan

ABSTRACT: In order to efficiently plan soil conservation measures it is necessary (i) to understand the impact of soil erosion on soil fertility with regard to local land cover classes and (ii) to identify hot spots of soil erosion in a spatially explicit manner. The aim of this study was to combine field observations on incidence of visible signs of soil erosion and soil organic carbon (SOC) content predicted from a soil spectral library in order to determine the state and process of soil degradation for specific land cover classes. Input data consisted of extensive groundtruth, a digital elevation model and Landsat 7 imagery from two different seasons. Soil spectral reflectance readings were taken from soil samples in the laboratory and calibrated to results of SOC chemical analysis using multiple linear regression techniques. The coefficient of determination for the model is promising ($R^2 = 0.78$). For an area with rugged terrain and small agricultural plots, decision tree models allowed mapping of soil erosion incidence and land cover classes at an acceptable accuracy level for preliminary studies. The various datasets were linked in the hot spot matrix, developed to combine soil erosion incidence information and mean SOC contents for uniform land cover classes in a scatter plot. The quarters of the plot show different stages of degradation, from well conserved land to hot spots of soil degradation. The approach helps to gain a better understanding on the importance of the impact of soil erosion on soil fertility and to identify hot spots. The results show evidence that on cropland seasonal vegetation characteristics are strong explanatory factors for soil erosion incidence and on grazing land fractional vegetation cover in combination with slope.

1 INTRODUCTION

The foothills of western Tajikistan consist mainly of easily erodable loess deposits. In the 1990's increasing poverty triggered by the civil war and the transformation of the economy lead to widespread cultivation of steep slopes formerly used as grazing land. In these areas water erosion is considered to be the fastest and most widespread soil degradation process (Sadikov 1999), also having a highly negative impact on soil fertility. In order to efficiently plan soil conservation measures it is necessary (i) to

understand the impact of soil erosion on soil fertility with regard to local land use/land cover types and (ii) to identify hot spots of soil erosion in a spatially explicit manner allowing to focus efforts. Satellite imagery provides information for soil erosion detection as well as for land cover classification and has therefore been the base of many spatial assessments of erosion during the past 30 years (Vrieling 2006). Ordinal classes of soil erosion from field observations have been linked to Landsat 7 (ETM+) data using decision tree models (Cohen *et al.* 2004). Soil organic carbon (SOC) is an important indicator for assessing soil fertility in dry ecosystems. Hill & Schütt (2000) found that it is positively correlated to growth conditions for cereal crops in dryland agriculture and shows strong correlation with qualitative erosion indicators. Soil spectral reflectance measured under standard conditions in the laboratory allows rapid prediction of SOC at low cost (Shepherd and Walsh 2002, Vagen *et al.* 2005). The aim of this study was to conduct a spatial assessment of erosion and its impact on SOC for specific land cover classes. The results provide the bases for preliminary land degradation assessments.

1.1 The study area

The three test areas of this study are situated mainly on loamy loess (Figure 1). The soils are defined as brown carbonate soils by the local Tajik definition system. Soils dominated by granodiorit mother rock are also situated in the study area. Typical values for SOC are 1–2%. CaCO_3 contents vary between 2 to 30%, depending on the mother

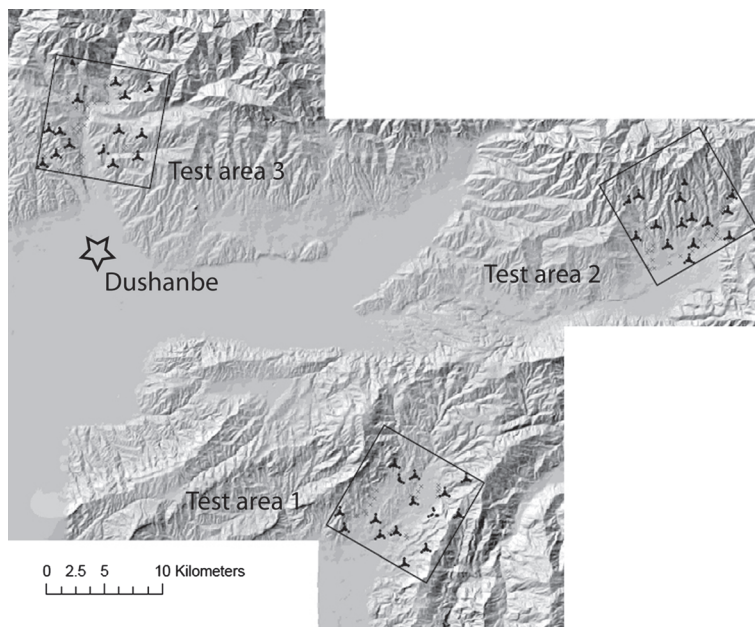


Figure 1. Overview on Central Tajikistan with the capital Dushanbe and the 3 test areas, each covering an area of 10 by 10 km. Within the test area the 15 clusters are displayed, each consisting of 13 sampling plots.

rock, but also on the state of erosion (Kuteminskij & Leonteva 1966). Rainfall characteristics vary from the South with 400 mm per year to the Northeast with up to 900 mm. Rainfall distribution is alike in the whole area and rainfall is concentrated during November through to April.

Topography can be described by valley floors (average slope = 7%), moderate hill slopes (average slope = 18%) and steep hill slopes (average slope = 35%). The main crop is winter wheat, both on the land of state farms on the valley floor as well as on hill slopes, where subsistence farmers are cultivating land. The fields are prepared (ploughed or harrowed either by animal traction or with machinery) in November when rain starts. In rotation (every 2–4 years) flax, chickpeas and beans are planted. Grazing land is often common land.

2 DATA

2.1 Raster data

Input data for the spatial assessment provided a digital elevation model (DEM) calculated from Russian topographic maps (scale 1:50 000, contour distance 20 m) and ETM+ imagery from two different seasons. The state of maximum vegetation activity is represented by an image dating from 24.05.2002 and the situation during the dry season and best visibility of bare ground is represented by an image dating from 22.08.2000. Satellite imagery rectification was performed using GPS ground control points measured in the field and additional control points extracted from Russian topographic maps. Residuals in x-direction were for both images on average 53 m, y-residuals amounted to 11 m for the image from 2002 and 20 m for the one from 2000 (Guntli, 2006). The atmospheric correction of the georeferenced images was conducted using ATCOR3 (Richter 2005).

The full dataset consists of the following data layers: Bands 1, 2, 3, 4, 5 and 7 of the two ETM+ scenes, band indices 5/4, 4/3 and 3/1, the optimised soil adjusted vegetation index (OSAVI) (Rondeaux *et al.* 1996), tasselled cap layers for brightness, greenness and wetness (Crist & Cicone 1984) as well as the DEM products slope and curvature.

2.2 Groundtruth

For efficient sampling of the full variation of land cover and soil characteristics over the study area, the ground survey campaign was conducted using a randomised systematic sampling scheme. It included 600 plots, clustered in groups of 13 plots. These clusters were again distributed over 3 test areas covering 10 by 10 km, each including 15 clusters (see Figure 1). Size of the observation plot was approximately 30 by 30 m. The extent of area with uniform land cover surrounding the observation plot was also recorded. The existence of visible signs of erosion processes, such as erosion rills, sediments in drains, pedestals, armour layer, plant/tree root exposure and tree mounds as described by Stocking & Murnaghan (2001) were noted in the field. Due to poor separability of erosion severity states, sample locations were separated into only two classes: Sites with visible signs of erosion and such without signs of erosion.

On each sampling plot topsoil (0–20 cm depth) and subsoil (20–50 cm depth) samples were collected as composite samples from two sampling pits, resulting in 1450 soil samples. Land cover characteristics, specifically fractional vegetation cover (FVC), were recorded at the stage of full vegetation development after the spring rains, and according to the FAO land cover classification system (Di Gregorio & Jansen 1998).

3 METHODS

Various statistical methods were used (i) to select the calibration data set with regard to spatial independence of observations, (ii) to predict SOC content from spectral readings by building a soil spectral library and (iii) to map field observations (soil erosion incidence and land cover types) based on the above described raster data sets. To determine state and processes of soil degradation a hot spot matrix was developed.

3.1 *Selecting the calibration sample set and focusing on test area 2*

Preliminary to the modelling, the calibration sample set and validity of information for the respective areas was examined. Due to the clustered sampling design, spatial autocorrelation among the samples had to be considered. Semivariogram analysis of slope, curvature, aspect and OSAVI data extracted for each sampling point was conducted in order to determine the minimal sampling distance at which spatial independence of observations can be expected. Independence was determined for sample points at a distance of 230 and more meters. Subsequently 7 samples per cluster were used as model input; the rest of the samples were used for validation.

The cultivated plots on the hill slopes are often extremely small. During field sampling 25% of the sample plots on cultivated land showed a uniform area around the target location that was smaller than 30×30 m. For 65% of the sample plots on cultivated land the area was between 30×30 and 100×100 m and only 10% were recorded as being larger than 100×100 m (1 ha). Sample plots smaller than 30×30 m were excluded from model calibration and validation, which improved modelling results considerably. Additional point information was extracted from the satellite image for the land cover types “aquatic” ($n = 33$) and “settlement area” ($n = 43$). These cover types are visually easily distinguishable on the image.

Climatic variances between the three test areas determine the state of vegetation and vegetation cover on a specific date and therefore also erosion processes. The recording date of the ETM+ dataset from May 2002 provides most information on erosion and erosion controlling factors for test area 2. For erosion incidence mapping the focus was therefore set to test area 2 only.

3.2 *Building a Soil Spectral Library*

The soil spectral library for prediction SOC was established following the procedure described by Shepherd and Walsh (2002). After sampling soil variability within the target area, soil spectral reflectance is measured under standard conditions in the laboratory. Air-dried and to 2 mm grinded soil samples were filled into Duran glass Petri-dishes and reflectance spectral readings were measured with a FieldSpec PRO FR

spectroradiometer at wavelengths from 350 to 2500 nm at an interval of 1 nm. Preprocessing of spectra included selection of every 10th nm and omitting bands with low signal to noise ratio. 272 samples out of 1450 were selected from principle component space for soil chemical analysis. For SOC analysis samples were pretreated with dilute HCl and subsequently analyzed by combustion in a CN analyzer. The resulting soil property data is then calibrated to continuum removed spectra by applying a multiple linear regression model (Seiler 2006).

3.3 *Decision tree modelling*

Pixel based classifications were elaborated based on decision tree models using the software CART (Classification And Regression Trees) (Breiman *et al* 1984), which is based on binary recursive partitioning (Steinberg & Colla 1995). The Gini splitting method was applied. The resulting models were implemented using the knowledge classifier of ERDAS Imagine software (ERDAS 2003). Information from raster data (satellite imagery and topographic information as described above) was extracted for each sampling point. In order to increase spatial reliability of extracted information, reflectance values from neighboring pixels were interpolated for each sampling point. But this procedure did not improve model results and the data was not used. Decision tree modelling was applied to map soil erosion incidence as well as land cover types. 8 land cover types were distinguished: Aquatic (rivers, streams), settlement area, annual cropland, cropland with permanent grass and forbs (this type includes mainly fallow cropland), land with dominant tree and shrub cover, grazing land with herbaceous vegetation and $FVC < 30\%$, $30-75\%$ and $> 75\%$, respectively.

Originally it was planned to link SOC contents to satellite imagery information, too. Because of limitations due to the small number of available samples attributed to brown carbonate soils, SOC was not mapped within this study.

3.4 *Hot spot matrix*

A simple approach, the hot spot matrix, was developed to estimate state and processes of soil degradation for uniform land cover classes. For the respective land cover class average SOC contents predicted from the soil spectral library and percentage of area showing erosion estimated from the soil erosion incidence map are plotted on the x- and y-axes of a scatter plot. The scatter plot is then divided into quarters showing (A) well conserved land characterised by a non-degraded state of soil resources (high SOC contents) and limited soil erosion processes, (B) land that may have been subject to land use changes and is characterised by a non-(not yet) degraded state of soil resources and widespread soil erosion processes, (C) land with marginal resources or soil resources subject to other degradation processes since SOC content is low but incidence of soil erosion is limited and (D) hot spots of degraded land, where SOC contents are already low and which is further degrading since erosion processes are widespread.

SOC content greater than 1.4% (corresponding to about 2% organic matter content) is considered to be high, representing non-degraded soil resources. If SOC is lower than 1.4% an impact of some degradation processes is likely. This corresponds with assessments carried out in the same areas and on brown carbonate soils

comparing SOC contents of soils not affected by soil erosion and soils showing various states of soil erosion (Jakutilov *et al.* 1963). If a specific land cover class shows incidence of soil erosion in less than 50% of the area, only limited erosion is expected for this land cover class, whereas land cover classes with incidence of soil erosion on more than 50% of the area are considered to be subject to widespread erosion processes.

4 RESULTS AND DISCUSSION

SOC content of brown carbonate soil samples was predicted using the spectral library approach. Decision tree models for mapping soil erosion incidence and land cover types were applied to the whole study area (land cover classification) or only to test area 2 (soil erosion incidence map). Subsequently the hot spot matrix was plotted for test area 2 and analyzed for explanatory patterns.

4.1 *Soil spectral library for soil organic carbon (SOC) contents*

For calibration of soil property data to soil spectra 166 samples attributed to brown carbonate soil were available. A third of the samples were randomly selected as holdout samples and used for validation. The multiple linear regression modelling showed good results with a final model with coefficient of determination for the total sample set of $R^2 = 0.78$ (calibration sample set $R^2 = 0.74$ and validation sample set $R^2 = 0.81$). The root mean square error is 0.354 for the calibration and 0.330 for the validation data set (Seiler 2006). This result is very promising with regard to applications of soil spectral libraries for land degradation assessments in the future.

4.2 *Soil erosion incidence map*

The soil erosion incidence model was developed for test area 2 only, for which satellite imagery available provided most information. The model distinguishes between areas with and without incidence of erosion. Accuracy of decision tree models showing soil erosion incidence was not satisfying when cropland was predicted along with grazing land. Therefore two very simple decision tree models were applied. For areas classified as cropland a single rule was most effective: If band 7 of the May 2002 imagery is smaller or equal to reflectance value 53 no erosion was predicted, otherwise it was classified as area showing erosion. For areas classified as grazing land, three variables were found most effective in splitting the data into nodes, where cases of erosion or no erosion prevailed; band ratio 4/3 of the May 2002 imagery, slope and tasselled cap wetness information from the August 2000 image.

The soil erosion incidence model as a whole (cropland and grazing land) was validated. The calibration data yielded a total accuracy of 77%, specificity is 67% and sensitivity 84%. The validation data set yielded a total accuracy of 53% only (specificity and sensitivity = 53%). If samples from the land cover type “land with dominant tree and shrub cover” are excluded, the total accuracy increases considerably (specificity and sensitivity = 62%). This land cover type covers a high variability of land management types, ranging from terraced orchards over vineyards where wheat is being intercropped

to heavily grazed rangelands. Therefore soil erosion incidence can not be predicted accurately for this specific land cover type.

41% percent of pixels of test area 2 (covering an area of 10 by 10 km) are classified as “without incidence of erosion”, 51% are classified as showing incidence of erosion. The rest (8%) of the area, aquatic or settlement area had been excluded from soil erosion modelling.

4.3 *Land Cover Classification*

The result of the land cover classification is a decision tree with 18 final nodes. Band 4 of the May 2002 image allows splitting off aquatic area and grazing land with low FVC, showing river sediments and soils with high amounts of iron oxides. The iron oxide index from the August 2000 image then splits of settlement area, which is dominated by tin roofs. The rest of the samples are classified by the tasselled cap greenness information from the August 2000 as well as the May 2002 imagery into groups characterised by land cover seasonality and FVC. Further, band 3 of the May 2002 is a powerful splitter to distinguish between areas showing different amounts of barren soil. Table 1 gives details on model validation. Accuracy levels for predicted land cover types are low, but overall land use types “cropland” and “grazing land” were identified at an acceptable level of accuracy (total accuracy for the validation dataset of test area 2 is 72%). Further more, final nodes and groups of final nodes of the decision tree model provide useful information on seasonality and FVC for samples belonging to the respective node. The nodes resulting from the decision tree model are subsequently called land cover classes.

4.4 *Hot spot matrix – State and processes of soil degradation for specific land cover classes*

For each land cover class mean SOC content and coefficient of variation (CV) (predicted from the spectral library for samples of the respective class) and the percentage of erosion incidence (zonal statistic for each land cover class extracted from the soil erosion incidence map) were calculated and added to the scatter plot of the hot spot matrix. CV of SOC is high within most of the land cover classes (mean CV for cropland is 27% and for grazing land 33%). This is not necessarily only a sign of a non-uniform classes of SOC content, but reflects the within field variation of SOC especially for grazing land. 53 sample pairs collected from a single sampling plot at a distance of around 7 m shows that the mean CV within fields is 23% for grazing land and 14% for annual and permanent cropland.

The pattern of the plotted land cover classes reveals that it is predominantly grazing land showing high percentages of erosion affected areas; nevertheless SOC contents on cropland is generally lower than on grazing land. This could either be pointing out that soil erosion is not the only degradation process going on on cropland, or could also be the result of biases in the field assessment, where visible signs of erosion on cropland are always harder to detect. SOC content on cropland varies not much, but erosion incidence a lot. Seasonal vegetation characteristics provide strong explanatory factors for these differences, while other factors, such as

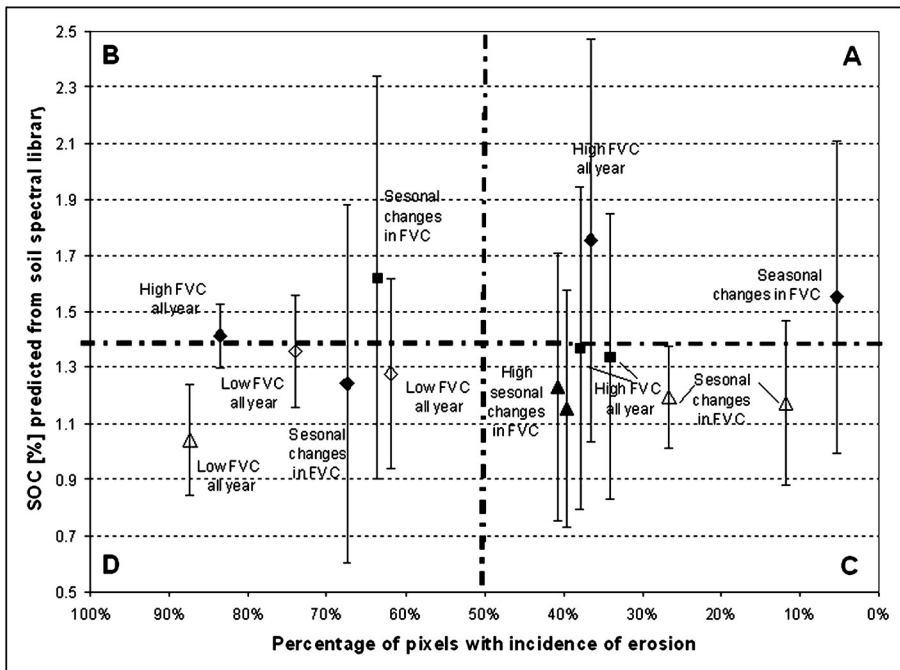


Figure 2. Hot spot matrix – Mean SOC content and CV (Y-indicators) plotted versus percentage of area showing incidence of erosion for each land cover class, for which SOC results were available. Symbols are representing the land cover types: White triangles = cropland annual, black triangles = cropland permanent, black squares = dominant tree and shrub cover, white diamonds = grazing land with FVC < 75% and black diamonds = grazing land with FVC > 75%.

slope, are not decisive: Land cover classes with high FVC during the growing season and moderate FVC during the dry season show least percentage of area with erosion. Land cover classes with high seasonal changes in FVC are typically intensively used farming systems on the valley floors. They show moderate percentage of pixels with incidence of erosion. Of most concern are areas with all year round low FVC coinciding to almost 90% with areas classified as showing erosion. Among the grazing land classes, classes with FVC < 75% are more prone to erosion than classes with FVC > 75%. But for grazing land seasonal vegetation and FVC characteristics can not explain all the differences in state and processes of soil degradation especially if FVC is moderate or low at least during parts of the year. Further analysis shows that slope steepness is then becoming the most crucial factor.

Grazing land with high FVC all year round can be picked out as the only well conserved land cover system (placed in quarter A). Land cover classes where soil fertility is on a high level but where widespread soil erosion may impact on soil fertility strongest, are grazing areas on steep slopes with moderate FVC (quarter B). Land cover classes placed in quarter C are stable at a low soil fertility level. In these areas it is not (only) soil erosion that impacts soil fertility, but other soil degradation types as soil fertility decline due to insufficient soil nutrient management are also of influence. The

Table 1. Number of samples (N), total accuracy and specificity for each land use (LU) and land cover (LC) type for the calibration sample set of the whole study area and the validation sample set of test area 2.

Land use type (LU)	Land cover type (LC)	Calibration data set of the study area			Validation data set of test area 2		
		N	Specificity LU [%]	LC [%]	N	Specificity LU [%]	LC [%]
Settlements	Settlement area	47	64	64	–	–	–
Cropland	Cropland annual	50	85	60	14	61	43
	Cropland permanent	30		47	9		11
	Trees/shrubs/rangeland	17		88	6		33
Aquatic	Aquatic (river, streams)	38	89	89	–	–	–
Grazing land	Grazing land FVC < 30%	6	67	100	2	80	50
	Grazing land FVC 30–75%	67		51	27		41
	Grazing land FVC > 75%	43		47	6		33
Total number of samples		298			64		
Total accuracy			75	61		72	36

hot spots placed in quarter D are land cover classes with low FVC all year round (cropland as well as grazing land). The highest percentage of area with erosion incidence (87%) and the lowest average SOC content (1.04%) shows annual cropland with all year round low FVC.

5 CONCLUSIONS

For prediction of SOC from spectral reflectance information a multiple linear regression model was established from continuum removed spectra. The coefficient of determination for the SOC model is for the total sample set $R^2 = 0.78$ (validation sample set $R^2 = 0.81$), which can be considered a sufficient level of accuracy for soil degradation assessments. For future assessments in the Tajik foothills, the spectral library elaborated will allow to predict SOC rapidly and cost effectively from soil reflectance readings.

This study showed that a spatial assessment of incidence of soil erosion and land cover based on ETM+ imagery in an area with difficult terrain and where small cultivated plots prevail is possible at a rather low accuracy level which is still acceptable for preliminary studies (validation $R^2 = 62\%$ for the soil erosion prediction model and validation $R^2 = 61\%$ for the land use types cropland and grazing land). Calibrating SOC content to ETM+ imagery was not possible; additionally to the constraints of the spatial and spectral resolution of the ETM+ image, the available number of brown carbonate soil samples was insufficient.

The modeling of land cover types yielded a decision tree with 18 final nodes. Even tough land cover types were not detected accurately, the final nodes of the decision tree model for land cover classification contributed very useful information on seasonality and FVC for the samples reflected by the specific node.

Estimation of soil erosion processes is likely to be improved by applying a soil loss model. Since topographic information is available at a more appropriate resolution than satellite imagery and land cover classification has yielded useful information on vegetation cover characteristics, improved results may be achieved when calibrating the (revised) universal soil loss equation (RUSLE) (Renard 1997) to the area.

The hot spot matrix developed for this study is a simple approach to determine state and trend of soil degradation of land cover classes with uniform land cover characteristics. It is a flexible approach, which can be used with data sets of various accuracy levels. The approach helps to gain a better understanding on the impact of soil erosion on soil fertility for land cover classes present in a study area and to identify hot spots of soil degradation caused by erosion. For test area 2 situated in the eastern part of the Tajik foothills there is evidence that on cropland seasonal vegetation characteristics are strong explanatory factors for soil erosion incidence and on grazing land it is FVC in combination with slope. On the land on the valley floor other degradation types than soil erosion are impacting on soil fertility.

ACKNOWLEDGEMENTS

Keith Shepherd from the World Agroforestry Centre (ICRAF) in Nairobi has given decisive methodological inputs for the study and he and his team have been very supportive with regard to any open questions. The Soil Science Research Institute of the Tajik Academy of Agricultural Science has been contributing to the study in scientific, administrative and organizational questions. The Remote Sensing Laboratory (RSL), Institute of Geography of the University of Zurich, provided the spectroradiometer. The investigations were supported by the National Centre for Competence in Research North-South (NCCR)/Work package 4, financed by the Swiss National Science Foundation (SNSF) and the Swiss Agency for Development and Cooperation (SDC).

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